

**Figure 1** Bright LED's small dimensions allow automakers to design CHMSLs (center, high-mount stop lights) into trunk lids, which, for some body styles, provides better visibility (top). Bright-LED brake lights provide greater safety by eliminating the 200-msec turn-on time tungsten bulbs require. Their size and low-temperature operation allow greater flexibility in tail-light design (bottom) (courtesy Fairchild Semiconductor).

# A THOUSAND POINTS OF BRIGHT

## turning up the volume on solid-state lighting

**A**DVANCEMENTS IN BRIGHT-LED-FABRICATION PROCESSES, device designs, and assembly technologies have been driving up LED-illuminator performance and driving down the cost of ownership at an impressive clip. Junction formulations, reradiating phosphors, and lens structures are all contributing to increases in efficiency and, as a result, attainable output (see sidebar “LEDs in the lab”). In the case of high-output white LEDs, improvements in broad spectral performance hold out hope for low-maintenance, energy-efficient light sources for general illumination.

Though LED efficiencies that rival standard fluo-

rescent lamps are still some time off, as Semiconductor Lighting Industry Association Chairman Yung S Liu, PhD, observes, “LED lights are also more environment-friendly since, unlike fluorescent lamps, they do not use mercury.”

The environmental advantages of solid-state lighting, both in its composition and its operating efficiencies, are not currently the principal market drivers, though they do imbue the technology and its purveyors with white-hat images.

Meanwhile, OEM designers and marketers working in a variety of sectors have been extending the practical range of applications for solid-state light-

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ing and carefully watching market acceptance. The fact that the end user's cost-benefit experience over the device's lifetime varies in ways that differ greatly from traditional lighting devices, however, complicates the market's value perception. A bright LED's significantly lower operating and maintenance costs than those for tungsten-filament and fluorescent bulbs offset the LEDs' high initial cost. As attractive as that observation might be on a spreadsheet, it makes for a hard sell in a consumer market in which a "price-first, everything-else-second" mindset dominates.

Complicating the high-volume rollout of high-output solid-state lighting devices is the fact that light-fixture manufacturers have not historically considered thermal management of the bulb in their designs beyond providing sufficient convection to ensure that a tungsten-filament bulb's high operating temperature presents neither a fire hazard to surrounding materials nor a burn hazard to people operating the fixture. Fixtures for bright LEDs, however, require some thermal planning if the resulting design is to optimize the LED's light output and operating life.

So, although you won't any time soon find bright LEDs crowding out traditional filament or fluorescent lamps on hardware-store and home-center shelves, the devices are making significant inroads in market segments such as automotive, traffic control, and exterior signage—all areas in which high efficiency and long lamp life add readily recognizable value.

### HIT THE ROAD

It is rare indeed to hear anyone use the phrases "early adopter" and "automotive segment" in the same sentence. Some might assert that such a juxtaposition is well on its way to oxymoronhood. But bright LEDs bring several compelling attributes to automobile makers, and, though the application is relatively new, their underlying traits derive mostly from the same principles and similar processes that produced their much older and well-proven cousins—LED indicators.

LED automotive tail, turn-signal, running, and brake lamps solve several significant limitations inherent to tungsten-filament incandescent lamps. Moderate levels of shock and vibration, part and parcel of the automotive experience, shorten filament life. Similarly, inrush

### AT A GLANCE

- ▶ Bright-LED drivers differentiate themselves among the various applications by output type, output amplitude, control method, and monitoring functions.
- ▶ Though LEDs are current devices—and bright LEDs are no exception—some applications, such as automotive tail, brake, and turn-signal lighting—can benefit from a voltage-drive topology.
- ▶ As more efficient LEDs become available, interior lighting for retail and residential applications will likely soon follow. LED manufacturers are only just beginning to address the problem of high-color-temperature light sources.

current, due to the filament resistance's positive temperature coefficient, hastens the bulb's demise. Thermal cycling, a significant feature in brake-light operation, tends to shorten incandescent-lamp life.

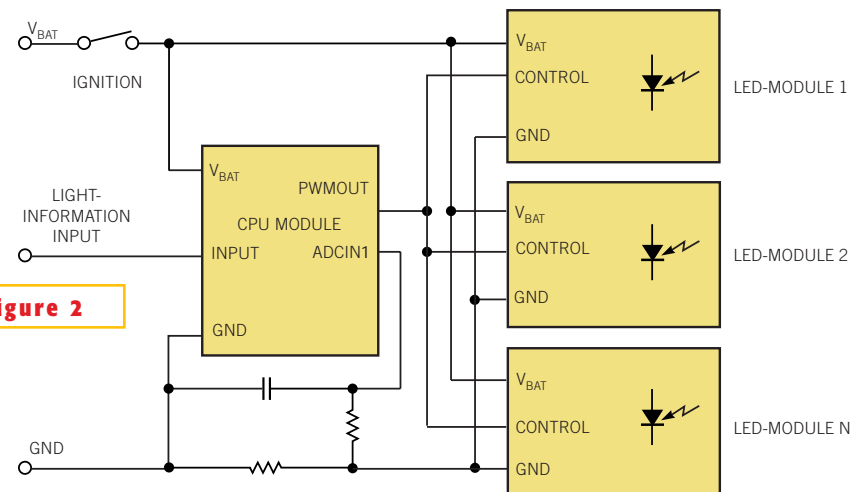
The incandescent bulb's inrush-current profile also complicates the task of circuit protection and fault detection. Automakers must set fuse ratings and fault-detection thresholds to currents high enough to accommodate the inrush-current magnitude and duration without nuisance fuse failures or false-positive fault detections.

LED structures, by contrast, are more robust than filaments in the presence of shock and vibration within the amplitude and frequency ranges that typify the automotive experience. Their low mass and small size limit the mechanical mo-

ment through which shock impulses and vibration can operate. The LED's size also allows automotive designers to fashion lighting functions into smaller spaces and into shapes that are more congruent with the vehicle's overall design. For example, instead of mounting a CHMSL (center, high-mount stop light) module on the rear deck, some vehicles take advantage of the LED's low volume requirements and incorporate the function in the trunk lid (**Figure 1**).

The automotive rear-exterior lighting-and-control application raises several interesting issues that may appear in other applications in which controlling and controlled devices are distant from one another. LEDs are essentially current devices. Electron-hole pairs recombine within an electro-emissive compound and, in so doing, emit a photon. An increase in current results in a corresponding increase in the recombination rate and in the optical flux output. The process isn't 100% efficient—hardly so—so an increase in current also increases the device's self heating through  $1-\eta$  power dissipation. Unless operating conditions are abusive, LEDs do not tend to fail catastrophically as do tungsten-filament lamps, but rather they tend to darken with age. Many device designers define an LED's end of life as the time at which the optical output falls to 50% of its initial value. Overcurrent and overtemperature conditions can hasten the LED's end of life, so most device manufacturers recommend that OEMs carefully control the LED's energy source.

These traits suggest that, to realize an LED's projected 11-year lifetime in an au-



A lighting-control module's CPU can monitor the combined current through several bright-LED drivers with one ADC input channel by measuring the sum of their ground currents (courtesy Melexis).

tomotive CHMSL or tail-lamp assembly, the vehicle's body-control module should operate the devices at constant current. However, as Analog Devices' automotive market specialist Bill Reidel explains, a constant-current design complicates the wiring between the body-control module and the lamp assembly and drives designers to remove the power-control IC

from the body-control module and place it into the lamp housing. A constant-voltage drive allows the control ICs to reside in the control module in which their fault-detection status information is needed and, in the same design, reduce the number of external components, fuses, and amount of wiring between the control module and the lamp housings.

Texas Instruments Automotive Applications Engineer Keith Wolford concurs: "One of the functions that the [LED-control IC] provides is that of a fuse. If you have the LED driver in the lamp housing, then you'd have to route power to that location and have it fused...whereas if you had a central lighting module, all you'd have to do is fuse the [power-

## LEDs IN THE LAB

According to the US DoE (Department of Energy), lighting consumes 23% of all electricity generated in the United States (Reference A). The department has funded a project with the aggressive goal to develop a solid-state light source with an efficiency of 200 lm/W based on GaN LEDs—a figure that compares strikingly with current lighting technologies, including white LEDs (Table A). The department estimates that such devices could account for electricity savings in excess of \$30 billion annually and reduce both oil imports and carbon emissions. The University of California—Santa Barbara and the Lighting Research Center at Rensselaer Polytechnic Institute (Troy, NY) are collaborating on the project.

Commercial R&D labs, including those at traditional bulb manufacturers, such as General Electric, Osram, and Philips, are pursuing nearer term goals. Commercially available white LEDs with efficiencies topping 40 lm/W should appear by the end of 2005 and 50 lm/W by the end

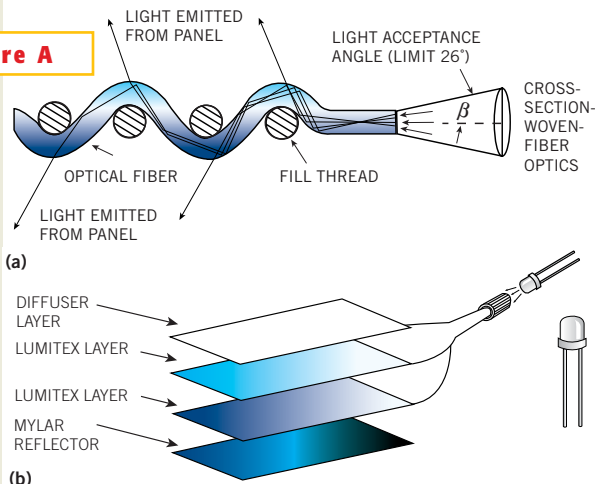
of the decade, according to Semiconductor Lighting Industry Association Chairman Yung S Liu, PhD.

A team from Lumileds Lighting and Agilent Technologies has reported narrow-spectrum devices with optical efficiencies topping 100 lm/W (Reference B).

Numerous small semiconductor companies that have specialized in indicator lamps—the LED's original commercial application—are also aggressively pursuing process developments and advances in device design for bright LEDs. Among the largest of these is Lumileds Lighting, whose Luxeon product line has led to a partnership it announced in November with Philips to supply the automotive sector—one of the largest of the early-adopting OEM segments.

Recent R&D efforts have not been limited to new LED devices and the power ICs to drive them. One challenge for many bright-LED applications is to distribute the light from a virtual point-source origin to a useful area without excessive attenuation.

Figure A



Lumitex's Light Engine distributes light from a woven fiber-optic bundle. Bending the optical fibers over precise radii distributes light evenly along the weave (a). A reflector behind the weave and a thin diffuser in front increase the optical efficiency and eliminate small residual variations in brightness across the surface (b) (courtesy Lumitex).

Diffusion is a common and effective approach in LED indicators and incandescent bulbs, but, historically, neither of those lamp types epitomizes the high-efficiency light source. Applications requiring projected light have used Fresnel collimators, but a technology that provides low attenuation has only recently emerged for applications that require even light distribution over a rectilinear area. Lumitex has combined bright LEDs, such as the Luxeon III Star and Luxeon V, a collimating lens, a fiber-optic bundle, and Lumitex's woven fiber-optic panels to form the Light Engine (Figure A).

Bending the fiber-optic strands over precise radii provides evenly distributed light exits along a strand length without scratching, stamping, or etching the

cladding. Despite the less-than-informative name, the Light Engine provides a bright radiating surface without the warm-up behavior or shock sensitivity of CCFLs (cold-cathode fluorescent lamps) and without the heat-generation and color-shift characteristics of incandescent lamps. Lumitex is commercializing the technology now with 3×5-in. panels selling for \$10 and up (OEM quantities).

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B. Ochiai-Holcomb, Mari, et al, "High-power truncated-inverted-pyramid (AlxGa1-x) 0.5In0.5P light-emitting diodes," Proceedings of the International Society for Optical Engineering, Volume 3938, pg 77.

TABLE A—POWER, EFFICIENCY, AND OPERATING LIFETIMES OF VARIOUS LAMP TYPES

Lamp type	Power (W)	Efficiency (lm/W)	Lifetime (kHrs)
Incandescent	15	8	1
Incandescent	100	15	1
Long-life incandescent	135	12	5
Halogen	20	12	3
Halogen	300	24	3
Compact halogen	50	12	2.5
Compact fluorescent	11	50	10
Fluorescent	30	80	20
Red LED	1	45	
White LED		30	100
White LED1		200	100

1. Project target set by US Department of Energy

supply feed] to that module. With the LED driver's diagnostic function, if the wire [to one of the lamp housings] shorted, then you can protect it with the electronics and not have to fuse each lamp-housing line."

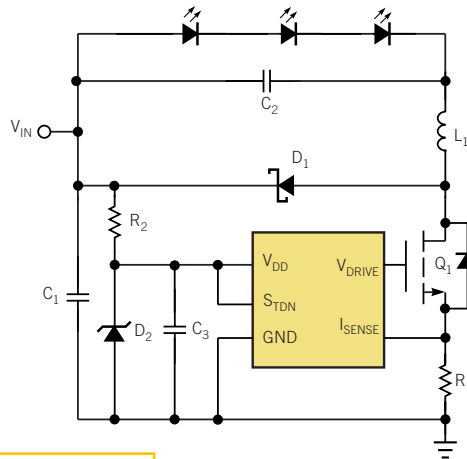
The AD8240 LED driver/monitor from Analog Devices embodies this approach. The device operates on 300  $\mu\text{A}$  with a supply range of 9 to 27V. A PWM input controls the lamp brightness allowing, for example, different daytime and nighttime minimum brightness levels in compliance with automotive regulations. An overcurrent-detection circuit, which comprises an external high-side current shunt and an on-chip comparator, latch off the output drive if the drop across the shunt exceeds a reference voltage—typically, 5V. The latch resets after each PWM cycle.

The shunt resistor and external PNP pass element limit the maximum load current. The manufacturer's recommended shunt resistance range, 0.1 to 0.5 $\Omega$ , corresponds to a maximum load current of 2 to 0.4A. The control module's microcontroller can monitor the load current by reading the IC's sense pin through an ADC-input channel. The \$1.15 (1000) AD8240 detects open-load, short-circuit, and partial faults, such as the case in which a single LED in a series string shorts. The driver/monitor IC is available in an MSOP-8.

In designs requiring a low-side controller, designers might consider the MLX10801 from Melexis, which can sink an absolute maximum of 550 mA peak and 400 mA average in an SO-8 package without an external pass device. A packaging option that carries an "A" suffix provides the same die in an MLPD-8 with a thermal pad, thereby reducing the  $R_{\theta\text{JA}}$  from 120 to 37K/W. This packaging modification raises the absolute-maximum peak and average currents to 1.2A and 750 mA, respectively.

A diagnostic pin allows a local microcontroller to monitor the load current through an ADC channel. Designs with more driver/monitor chips than ADC channels may sum the ground currents and monitor the total with a single analog input (Figure 2).

Melexis characterizes the MLX10801 with a suite of transient pulses, a 40V load dump, and crank-induced undervoltage conditions that represent expected non-standard operating conditions that the



**Figure 3** Zetex's ZXSC310 fits in a SOT-23-5 package and, in conjunction with an external pass element and a few other external components, make a compact controller/driver circuit for bright LEDs, replacing low-voltage halogen fixtures.

device must survive. A programmable nonvolatile data latch allows the OEM to enable temperature measurement through either an on-chip or an external sense diode. A control input allows PWM dimming—a common attribute of LED drivers. Holding the control input low for more than 32 msec forces the driver into its sleep mode, reducing its quiescent current from 2 mA to 105  $\mu\text{A}$ . Forcing the control input high for 8  $\mu\text{sec}$  initiates a wakeup sequence, which completes after no more than 300  $\mu\text{sec}$ .

### MAKING A SPECTACLE

LED-video displays for exterior signage use thousands of bright LEDs in the familiar RGB-pixel configuration. The power-management demands of dynamic pixel control, the power-dissipation challenge of such large and dense arrays, and the high-cost of maintenance or repair of systems in the field form an onerous combination of requirements for an OEM-display designer.

The TLC5922 from Texas Instruments exemplifies LED drivers suitable for this application, which places a premium on high channel density and a small package. In the 5922, TI delivers 16 channels in an HTSSOP-32 package. In addition to individual on- and off-state controls, each channel provides a programmable constant-current sink of 0 to 80 mA with a typical accuracy of  $\pm 1\%$ . One external resistor sets the maximum current output current; a separate dot-correction register controlling each channel allows the application to independently set

channel currents with a resolution of 128 steps.

Communication to the device is by way of a serial port that can support data transfers as fast as 30 Mbps. The multichannel driver includes two error flags. One, the LOD (LED-open-detection) flag, reports a broken LED on an output channel. The host processor can poll the LOD status for each channel by examining the serial-output bit stream that the driver reports each time the host clocks in new channel-on/off data. The TEF (thermal-error flag) indicates that the die temperature has exceeded the 160 $^{\circ}\text{C}$  threshold. If either an LOD or a TEF is active, the driver pulls down an open-collector output, Xdown. Applications can connect the Xdown pin from several drivers to one pullup resistor to generate a common interrupt signal—a useful feature in applications that require many channels.

The \$1.90 (1000) multichannel driver operates on 3 to 5.5V supplies but tolerates an LED-supply voltage as large as 17V on its outputs. The driver's quiescent current is highest at the lower extreme of its operating-temperature range. With the serial port clocking at full speed, an initial maximum of about 62 mA falls about 25 mA with a die-temperature increase to 25 $^{\circ}\text{C}$ . Between clock bursts, the quiescent current falls further to the neighborhood of 6 to 12 mA with a current programming resistance in the range of 1.3 to 10 k $\Omega$ .

Another emerging application for bright LEDs is as a replacement for low-voltage halogen lamps. Due to the common use of low-voltage halogens in groups sharing a common power-supply module, an LED-replacement system would benefit from a control circuit that could fit into the lamp housing. This approach would allow both direct-replacement and mixed-use installations.

Zetex's ZXSC310 is an example of such an LED-drive-control IC. Zetex packages the device in a SOT-23-5 and, with the addition of a few small external components, the 310 can light a series string of LEDs at peak currents well in excess of 500 mA (Figure 3). An internal sense voltage, nominally 19 mV, and an external fractional-ohm sense resistor fix the peak current.

The current ramp-up time,  $T_{\text{ON}}$ , is proportional to the peak current and the inductor value and inversely proportional

to the inductor voltage:  $V_L = V_{IN} - V_{LED}$ ; the ramp-down time,  $T_{OFF}$ , is fixed. Applications can operate the 40-cent (10,000) driver at frequencies as high as 200 kHz. Higher frequencies are possible with some reduction in efficiency. Between the ability to set the peak current and ramp-up time, applications can operate the 310 in either continuous or discontinuous modes. In the continuous mode, the time integral of the current-ramp rate is smaller than the peak current during the  $T_{OFF}$  interval, leaving a nonzero forward current at the beginning of the next  $T_{ON}$ . In the discontinuous mode, the forward-LED current reaches zero before the end of  $T_{OFF}$ .

Vishay offers a single- and dual-channel constant-current LED driver that can source 0 to 2A. The FX4040G711 single-channel and FX4040G721 dual-channel drivers require only one external component—a programming resistor—per channel when operating from maximum 20V supplies. A second external component—a capacitor—allows the input supply maximum to extend to 35V.

Vishay packages the FX4040G7s in 10×10-mm BGA-9s. The \$1.44 (10,000), single-channel- and \$2.16 (10,000), dual-channel constant-current drivers can operate over the -40-to-+85°C industrial-temperature range.

#### MORE THAN A FLASH IN THE PAN

Camera phones—the mobile-telephone industry’s latest way of trying to sell highly profitable (read: significantly overpriced) data traffic—re-

quire a flash source to operate under low-light conditions. But mobile phones afford far too little space to include xenon flash tubes and their associated drive electronics. The application also generally does not demand the 1- $\mu$ sec flash performance xenon affords; flash durations of a few milliseconds suffice. Instead, phone makers have turned to white LEDs as flash sources. Unfortunately, many models excite the flash LED with only a few hundred milliamperes—enough to look like a flash but not enough to be effective. To generate more than a “marketing flash,” LED-drive electronics must supply a current of 0.5 to 1A or more and occupy as little interior volume as possible.

Several IC manufacturers are addressing the need for higher current flash drivers, though not all are taking the same architectural approach to solving the problem, as parts from Austriamicrosystems and Linear Technology exemplify. The 1A Austriamicrosystems AS3683 charge pump includes gear-shifting among 1, 1.5, and 2× pump ratios. The 3683 provides two means of controlling the flash current. A serial interface provides a “soft-flash” mode in which a microcontroller performing peripheral management can set the current over a 15-mA to 1A range. A hardware-control mode allows an application to select one of eight currents using three input pins, reducing the software overhead. In this fashion, a flash system can switch between preview and flash currents by signaling as few as two wires.

The \$1.80 (1000) driver also provides independently programmable preview and flash durations as long as 800 msec in 100-msec steps. The application can initiate either the preview or the flash intervals through the serial port, the hardware port, or separate preview and strobe pins. The QFN-24 package provides sufficient I/O flexibility to separately address six LEDs as two groups of three devices.

The LTC3453 buck-boost converter from Linear Technologies not only differs in power-conversion architecture, but also takes the opposite approach to the control interface. The 3453 delivers 500 mA to an LED flash from a DFN-14 package and a minimalist’s two-pin control interface. The driver provides two preview, or “torch,” modes; a flash mode; and a shutdown mode. Two resistors set the currents for the three active modes—the two torch modes directly and the flash current as the sum. The manufacturer recommends values for 150, 350, and 500 mA, respectively. The driver’s residual current in shutdown mode is 6  $\mu$ A.

With a minimum input-voltage requirement of 2.7V, the \$2.10 (1000) IC can drive one to four LEDs through the full charge cycle of one lithium-ion cell. A power pad on the package’s underside simplifies the flash subsystem’s thermal design. The device provides protection against open- and short-LEDs and thermal overload. □

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